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Autonomous Navigation Performance During The Hartley 2 Comet Flyby

EPOXI Mission

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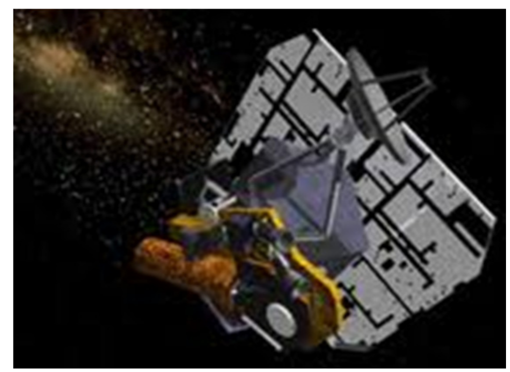


Autonomous Navigation

What?

- The capability to estimate a spacecraft trajectory and calculate maneuvers entirely onboard

Why?

- During high-dynamics events, ground-in-the-loop navigation is not practical due to long transmission and ground processing times

How?

- Optical measurements are recorded by a spacecraft camera

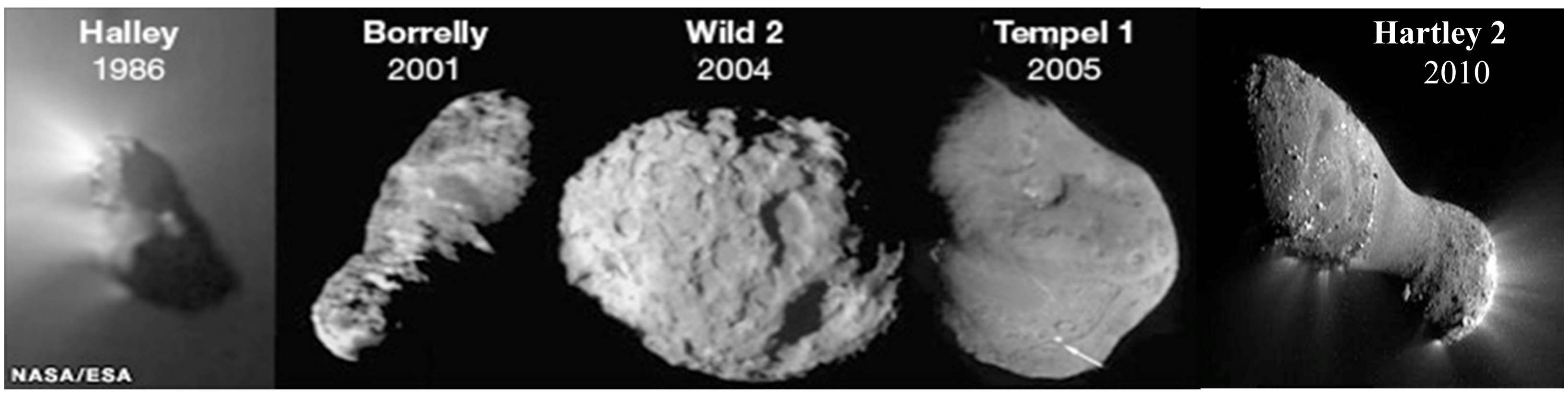
Implementation on EPOXI mission

- AutoNav C-based software package performs **image processing**, **state estimation**, and **maneuver calculation** onboard
- Attitude control uses AutoNav trajectory solution to point instruments

Comet Flybys

- AutoNav is critical to small body flybys
  - Small body ephemerides are not known accurately prior to flyby
  - Time of flight errors cannot be resolved until parallax is observed in observations near closest approach
  - Without AutoNav trajectory updates, the comet nucleus must be captured as a mosaic by scanning the camera across the sky
- EPOXI Hartley 2 Flyby Requirements
  - Continuously track comet nucleus in 10-mrad field of view
  - ± 3.5 km trajectory knowledge, ± 0.3 seconds time of flight knowledge

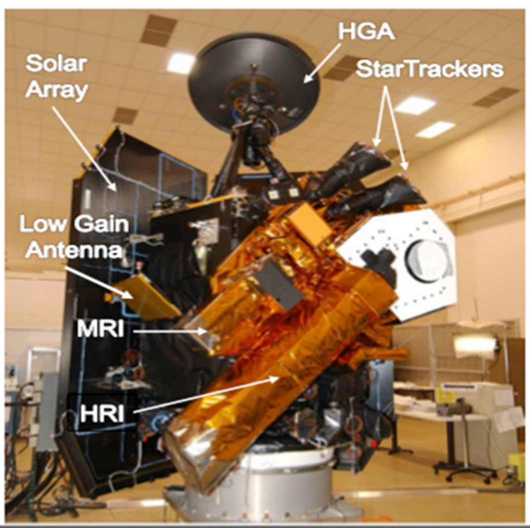
Giotto | Deep Space 1 | Stardust | Deep Impact | Deep Impact/EPOXI



Brightness Tracker | AutoNav 40 m/pixel | AutoNav 14.5 m/pixel | AutoNav 7 m/pixel | AutoNav 7 m/pixel

EPOXI Mission Challenges

- Reuse of Deep Impact Spacecraft with new objectives
  1. Imaging is **continuous** through 700km closest approach (180° slew)
  2. Hartley 2 is **smaller**, more **active**, rotating **faster**
  3. Relative flyby velocity is **faster**
  4. Different Sun-Comet-S/C geometry
- Attitude bias errors cannot be estimated using Deep Impact version of AutoNav
- Center of brightness observation is offset from true center of mass
- **Goal**: Track comet nucleus in camera continuously through closest approach



	Tempel 1	Hartley 2
Primary Objective	Observe impact	Observe nucleus
Observation Gap	E-50 sec to E+40 min	No Gap
Comet Size	7.6 km x 4.9 km	2.2 km x 0.5 km
Comet Period	40.7 hours	18.1 hours
Relative Velocity	10.2 km/s	12.3 km/s
Solar Phase Angle at Closest Approach	64°	77°
Max Resolution	7 m/pixel	7 m/pixel

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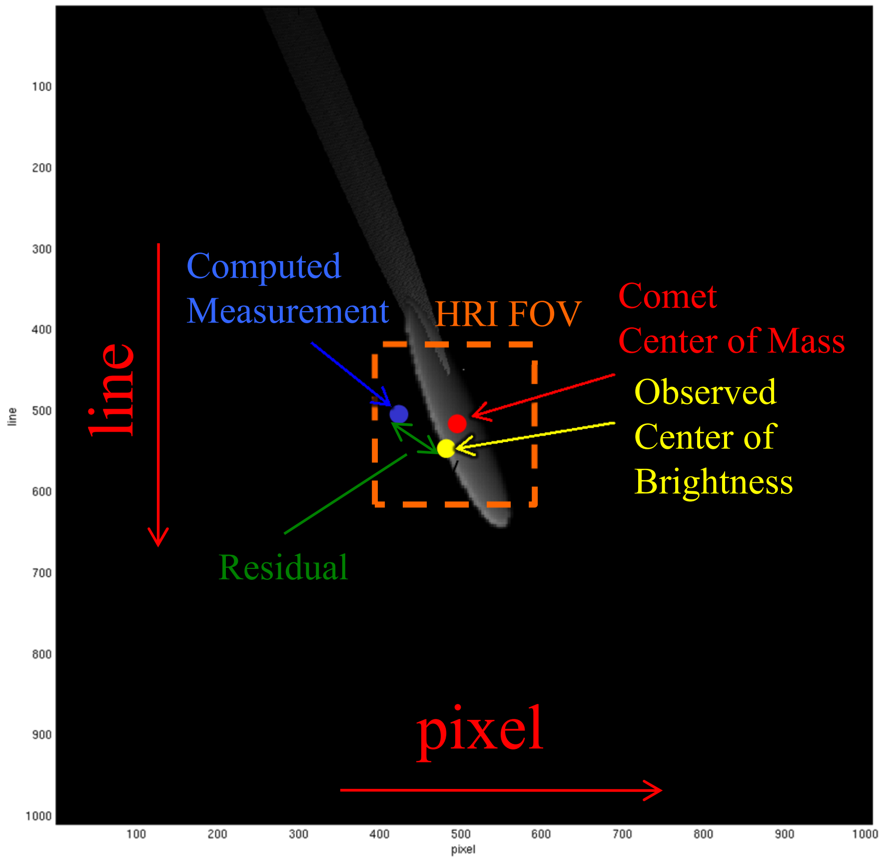
Optical Measurements

Simulated MRI Field of View



Sliding Data Arc:

Arc Length

Max Data History — Now

- Cameras
  - Medium Resolution Imager (MRI): 10-mrad FOV
  - High Resolution Imager (HRI): 2-mrad FOV
  - 1024 x 1024 pixel CCD
- Observed-Computed Residuals in MRI Pixels:

Residuals =

Observed (p,l) – Computed (p,l)

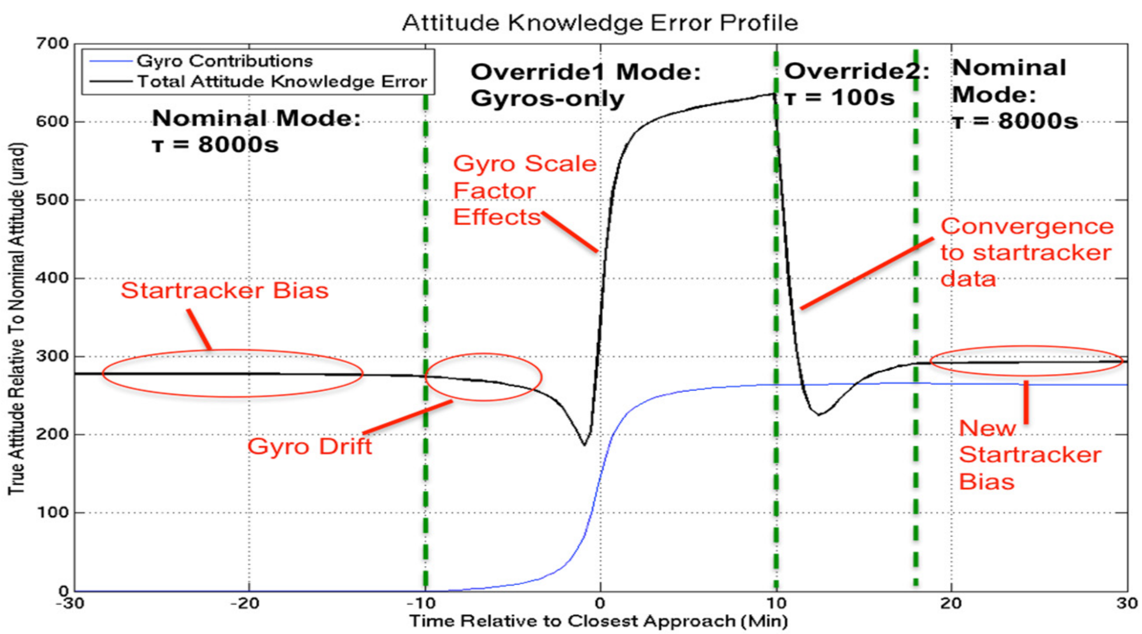
Camera Model

Predicted Position

Reported Attitude

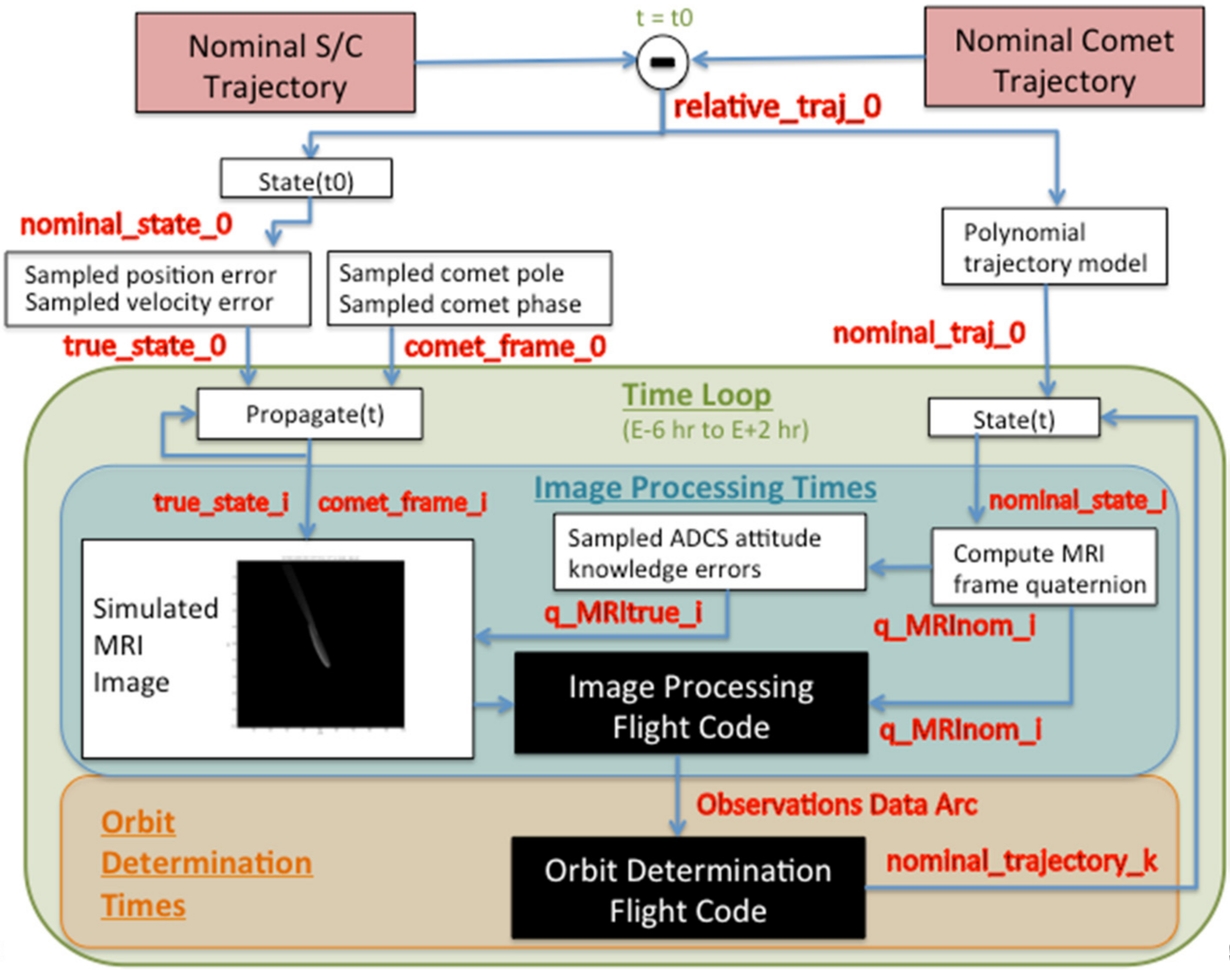
Uncertainty Sources

1. Position/Velocity errors in ground-based S/C and comet trajectories
2. Comet pole & phase
3. Attitude knowledge errors
   - Ability of startracker & gyroscope instruments to estimate attitude
   - Modes: Nominal (Startracker τ=8000s), Override1 (gyros only), Override2 (Startracker τ=100s)
   - Startracker error is primarily a bias
   - Gyroscope errors include drift, scale factor, and misalignment effects



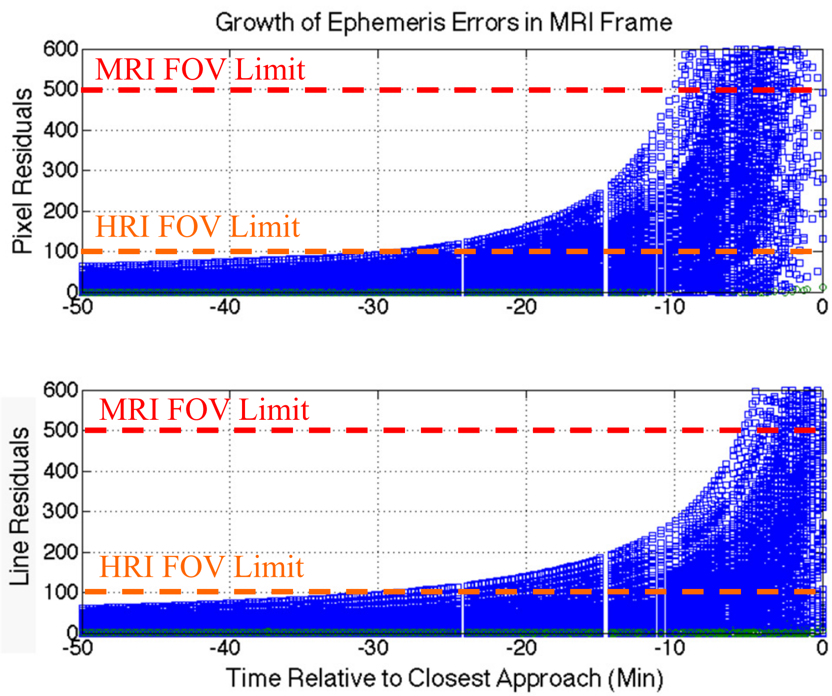
Monte Carlo Simulation

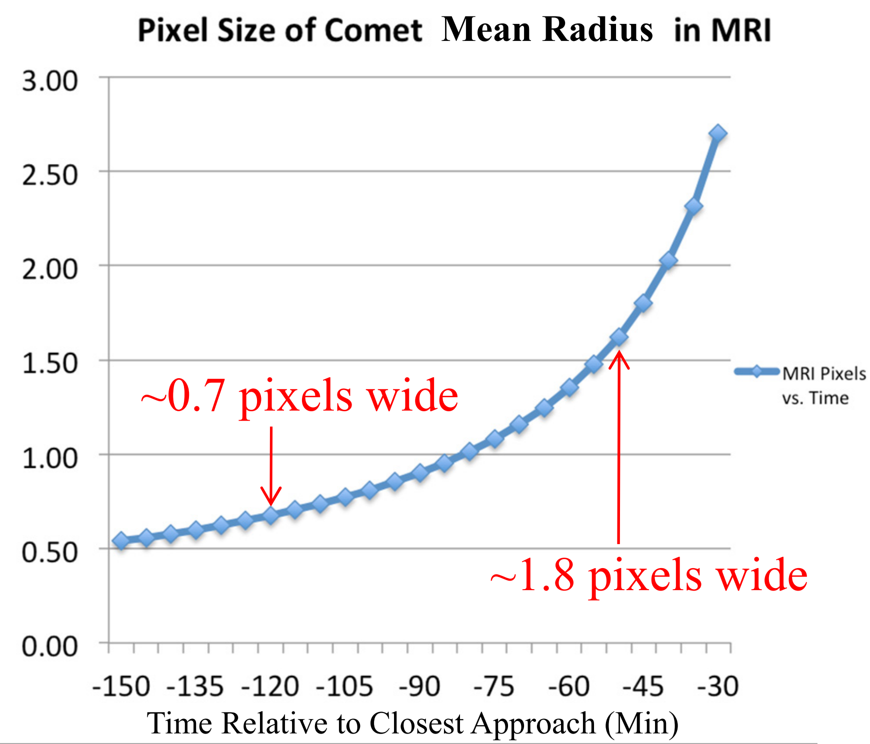
- Monte Carlo simulation directly applies user-defined **uncertainty models** to the **simulated image** and **attitude** data processed by the **flight code**.
- Output: 3-σ observed-predicted residuals in camera pixels



Approach Phase

- Approach characterized by transition from ground-based trajectory to AutoNav
- Determination of AutoNav start time is a trade between **signal strength** and the penalty of **stale ephemeris errors**.
  - Imaging commenced at E-50 minutes with a 15 second cadence
  - Orbit determination (OD) updates commenced at E-42 minutes with a 1 minute cadence





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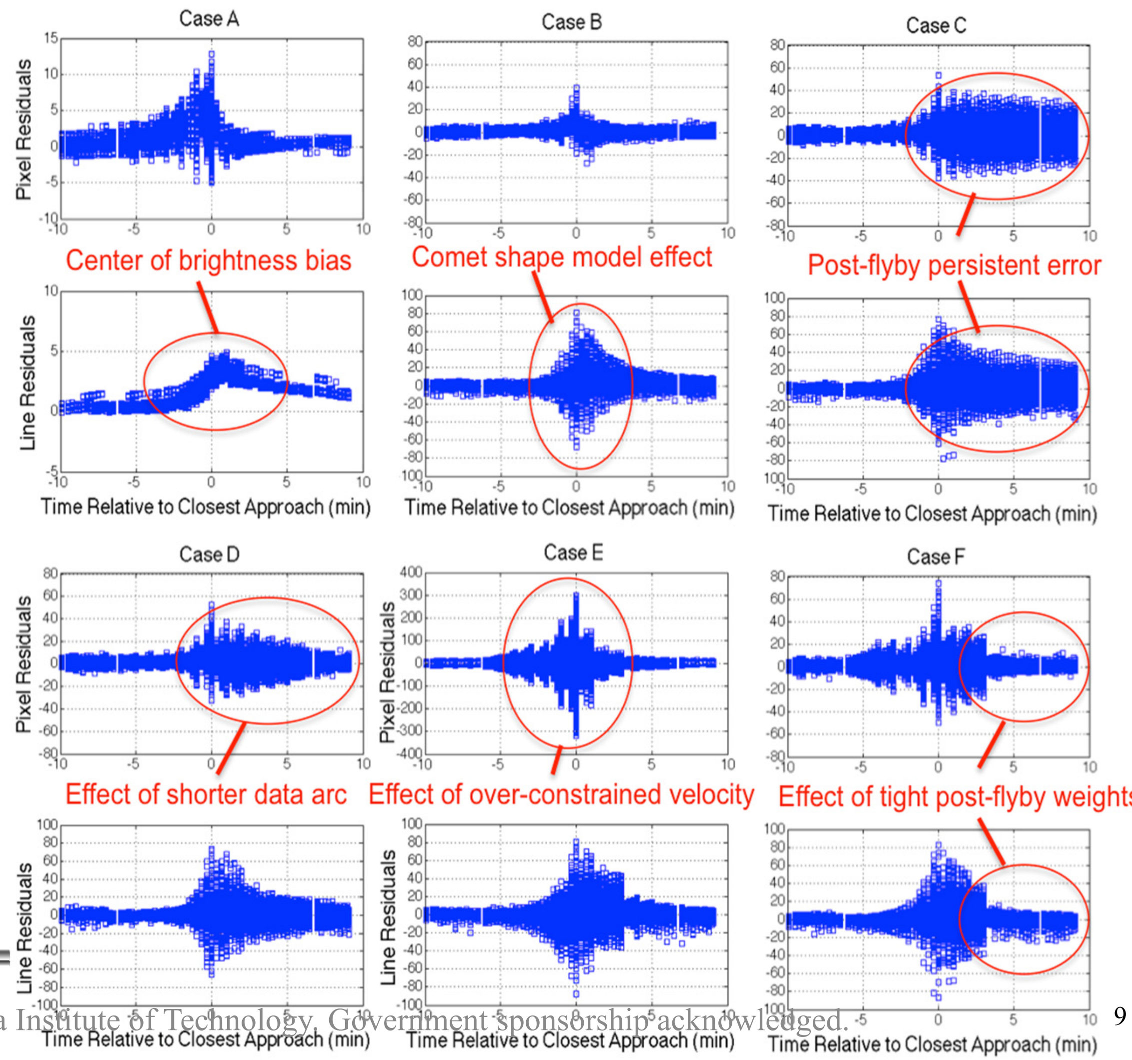
Encounter Phase

- Encounter characterized by 180° slew through closest approach
- Pre-flyby and post-flyby measurements **do not match** a dynamic trajectory model due to **center of brightness offset** and **attitude errors**

Case	Comet Shape	Att Errors	OD Arc Length	Blobber Weight	Centroid Weight	Velocity Sigma
A	0.4km x 0.4km x 0.4km	Off	20 min	15 px	15 px	0.5 m/s
B	2.2km x 0.5km x 0.3km	Off	20 min	15 px	15 px	0.5 m/s
C	2.2km x 0.5km x 0.3km	On	20 min	15 px	15 px	0.5 m/s
D	2.2km x 0.5km x 0.3km	On	8 min	15 px	15 px	0.5 m/s
E	2.2km x 0.5km x 0.3km	On	8 min	15 px	100 px	0.5 m/s
F	2.2km x 0.5km x 0.3km	On	8 min	15 px	100 px	2.0 m/s



Filter Adjustments

- Case D: Reduce arc length to **8 min**
- Case E: Adjust filter weighting of optical data to **100 pixels** from E-7min to E+2min
- Case F: Adjust filter velocity sigma from 0.5 m/s to **2.0 m/s**

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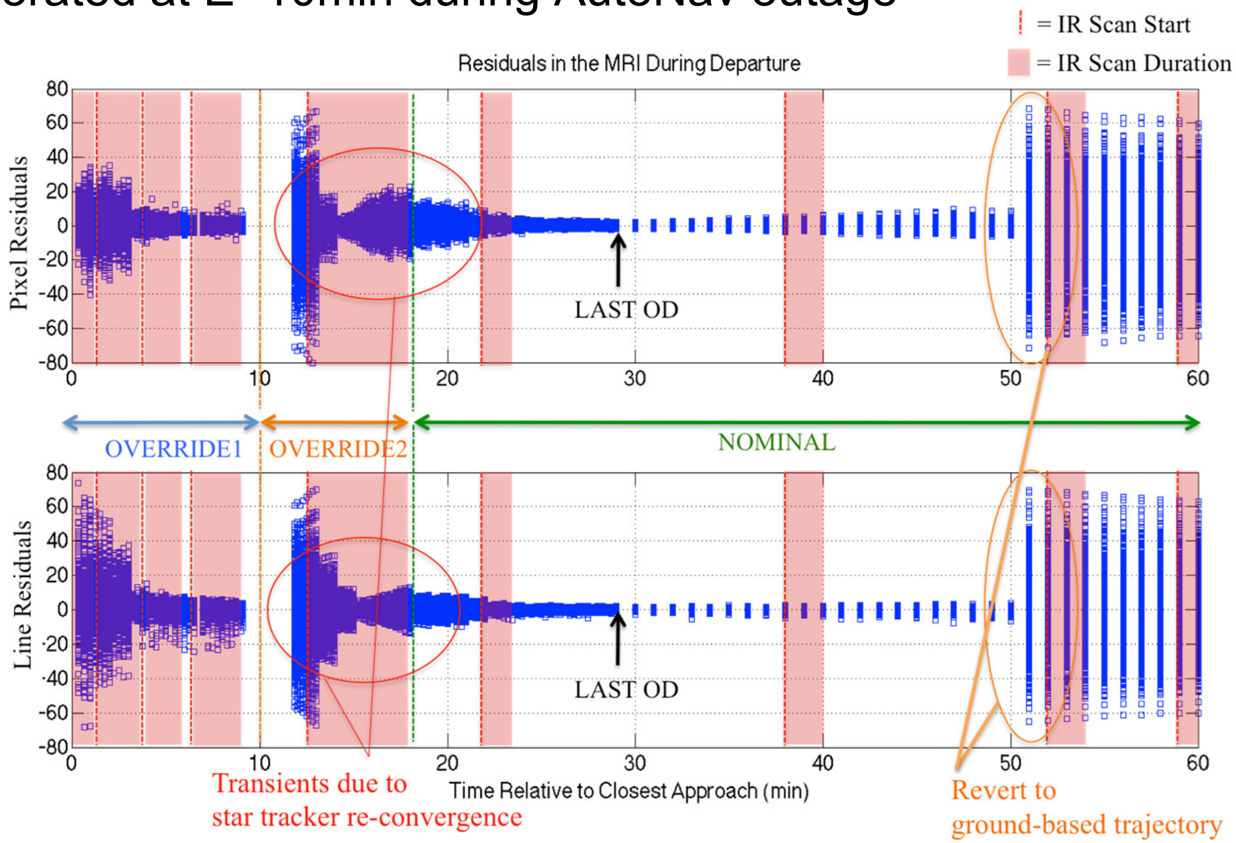
Departure Phase

- Departure characterized by system recovery after the 180° encounter slew
  - Determine AutoNav end time and transition to ground-based trajectory
  - Correct the gyros-only attitude solution with startracker data
  - Allow sufficient time for AutoNav to react to attitude correction
  - Minimize the pointing impact during the post-flyby IR scans.
- Star trackers reincorporated at E+10min during AutoNav outage

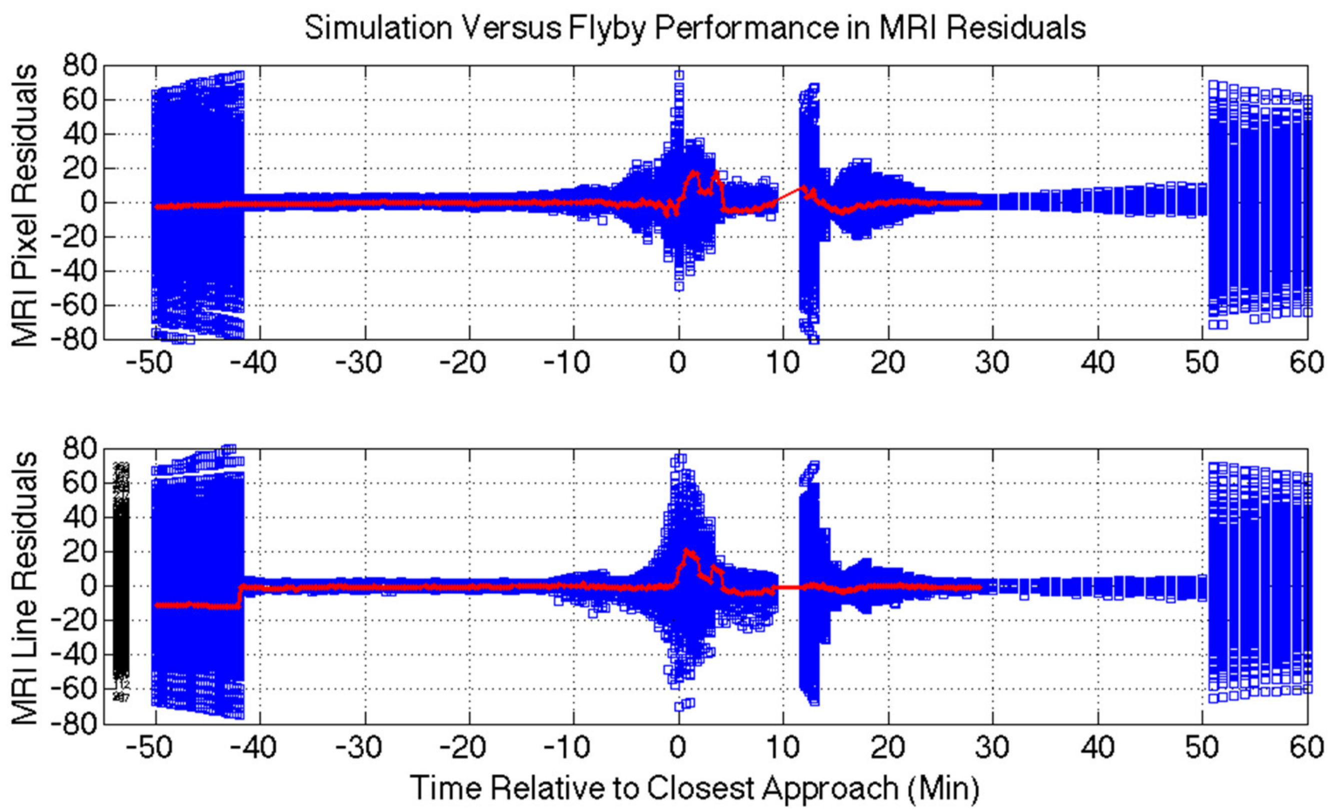
Departure Configuration

- E+10min:
  Override2 Mode (τ=100s)
- E+18min:
  Nominal Mode (τ=8000s)
- E+30min:
  Final OD Update
- E+50min:
  Transition to ground-based trajectory

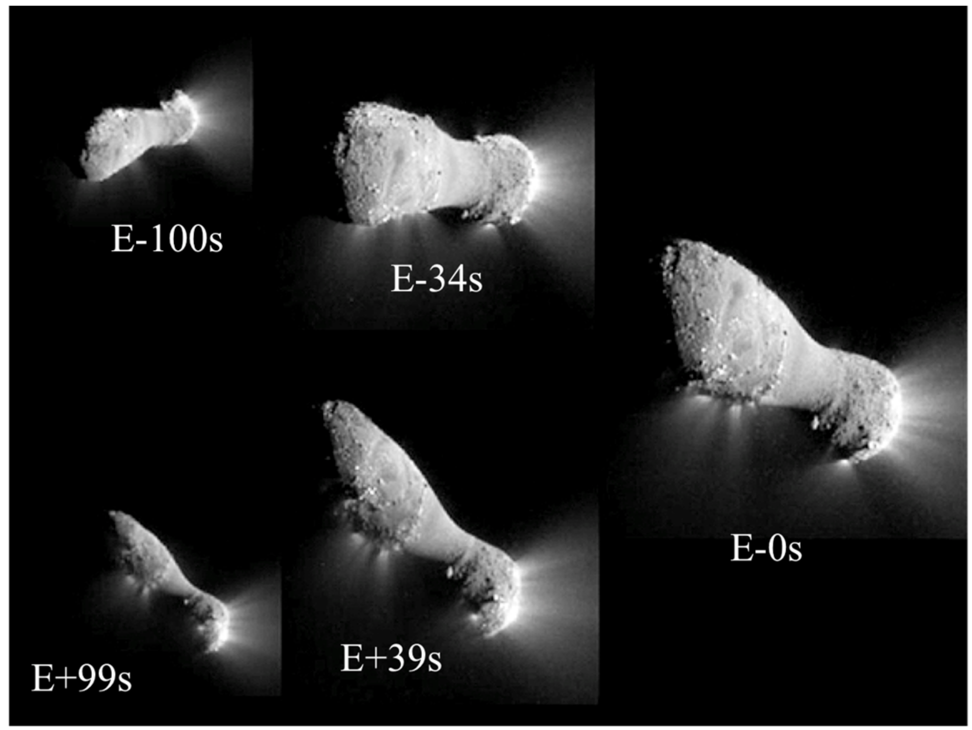


Flyby Performance

- AutoNav flyby performance well characterized by Monte Carlo simulations
- First OD update corrects 1 pixel in the pixel axis, 12 pixels in the line axis
- Maximum residual of ~20 pixels observed at E+1 min
- ~10 pixel residual during attitude convergence on departure



EPOXI Hartley 2 Images



Questions?

Flyby Video

BACKUP

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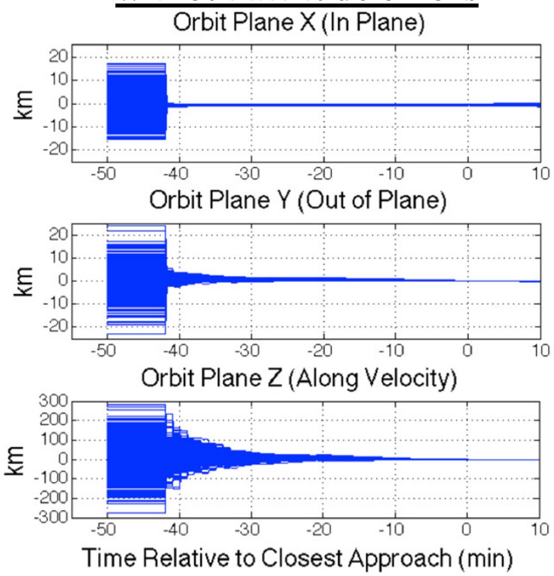
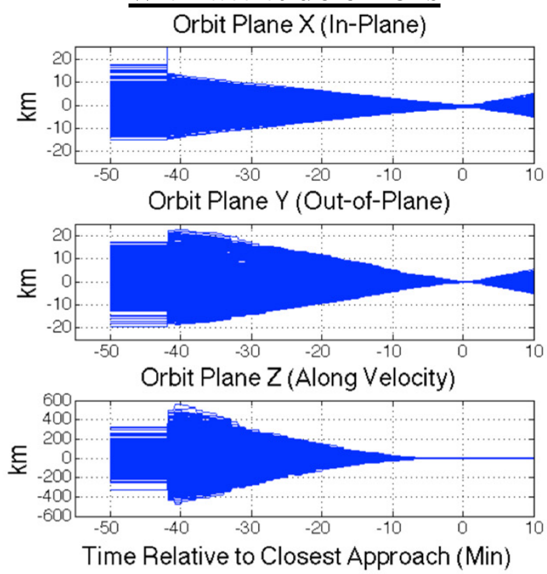
Attitude Issues

- No capability to estimate attitude knowledge bias errors with the version of AutoNav flying on the Deep Impact spacecraft
- Attitude knowledge errors absorbed into position & velocity estimates
- Position and velocity error estimates combine to create a fixed bias profile in the camera

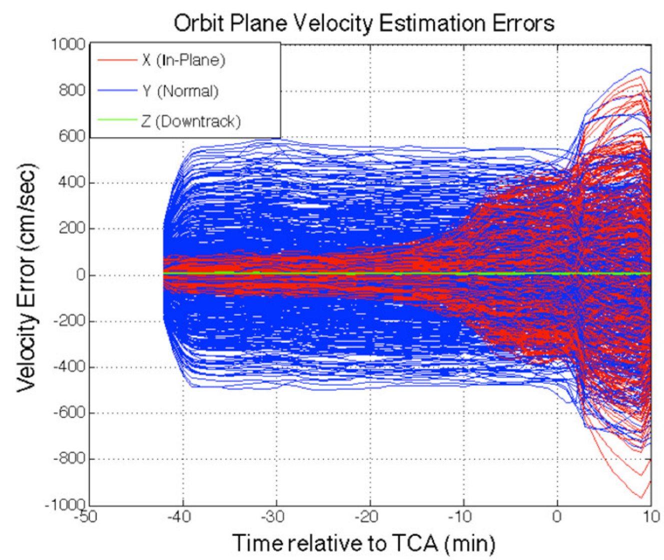
Position estimation errors without attitude errors



Position estimation errors with attitude errors



Velocity estimation errors with attitude errors



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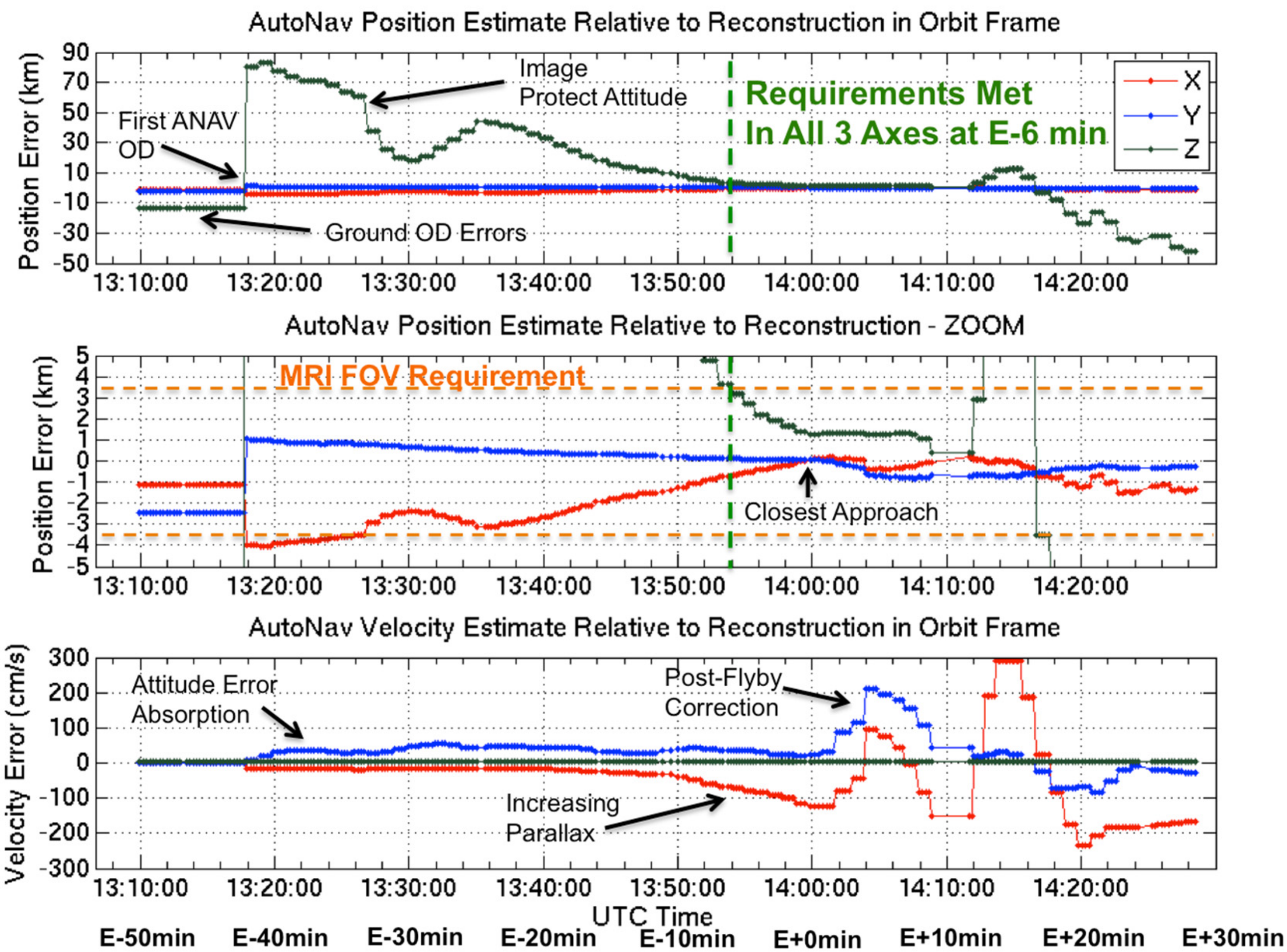
Flyby State Errors



Error Models

Error Model	3-σ Uncertainty	Distribution
Position Crosstrack	20 km	Gaussian
Position Downtrack	300 km	Gaussian
Velocity Crosstrack	5 cm/s	Gaussian
Velocity Downtrack	5 cm/s	Gaussian
Comet Pole RA	360 deg	Gaussian
Comet Pole DEC	180 deg	Gaussian
Comet Phase	360 deg	Gaussian

Error Model	3-σ Uncertainty	Distribution
Startracker Bias	300 urad, each axis	Uniform
Star Changeout	100 urad, each axis	Gaussian
Startracker temporal noise	50 urad, each axis	Gaussian
Gyro Drift	500 urad/hr, each axis	Gaussian
Gyro Scale Factor	183 ppm, each axis	Gaussian
Gyro Misalignment	80 urad, each axis	Gaussian